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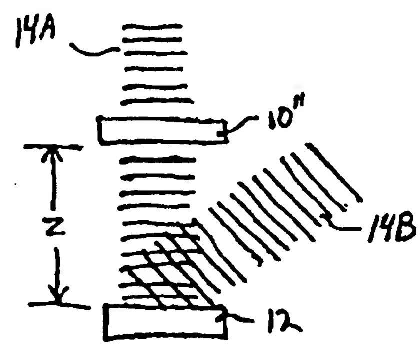
(57) Abstract



Methods for forming holographically processes polymer-liquid crystal composites (HPP7LCC) films and electrically switchable gratins utilizing HPP/ICCS are disclosed. These involve imaging a complex mask (10') which may be computer generated, containing the pattern to be imaged onto a film (12) of an HPP-LCC by use of a pair of interfering wavefronts (14A, 14B) as shown in the figure. By suitably selecting the angle between the pair of interfering wavefronts (14A, 14B), a desired submicron holographic pattern can be formed in the HPP/LCC film (12) in order to achieve optimum diffraction efficiency, with the pattern being modulated by the pattern in the mask to achieve the desired optical effect. Alternatively, the imaging may use contact lithography, where the mask (10') is in direct contact with the HPP/LCC film (12) as shown in figure 2 or the mask may be a focussing Fresnel element (10) as shown in figure 3.

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OPTICAL COMPONENTS CONTAINING COMPLEX DIFFRACTION GRATINGS AND METHODS FOR THE FABRICATION THEREOF

Field Of The Invention

This invention relates to optical components and methods for the fabrication thereof and more particularly to the fabrication of a particular class of holographically processed polymer/liquid crystal composites (HPP/LCC) containing complex diffraction gratings and optical components utilizing such HPP/LCC's.

Background Of The Invention

Optical technology has established many uses for diffractive optical elements, including both thin (Raman-Nath) diffractive elements and thick (Bragg) gratings, and volume holograms. both in free space and guided wave optical geometries. Two examples of applications in a free space geometry are diffractive lenses and transmission diffractive elements to distribute laser radiation into a desired pattern. Applications in a waveguide geometry include coupling from guided to radiated modes. Bragg reflectors or wavelength filters, and coupling between guided modes of adjacent waveguides in an integrated optical circuit. In previous technology, such diffractive elements are typically static in their behavior.

Recent advances in materials science have led to a new family of volume hologram Bragg gratings that are electronically switchable; that is. their power to diffract light may be adjusted or switched, ideally between 100% and zero, by application of an electric field. For purposes of this application. the following definitions relating to these advances will apply:

"Holographically processed polymer/liquid crystal composite or HPP/LCC" is defined as the composite material system resulting from the method of polymerizing mixtures of polymer, liquid crystal and other ingredients using interfering laser wavefronts in order to produce a captive distribution of microdroplets, as described for example by Sutherland et al and Margerum et al in the following:

1. R. L. Sutherland, L. V. Natarajan, V. P. Tondiglia, T. J. Bunning. Bragg Gratings in an Acrylate Polymer Consisting of Periodic Polymer-Dispersed Liquid-Crystal Planes, Chem. of Materials, 1993, 5, 1533.38.

2. R. L. Sutherland, L. V. Natarajan, V. P. Tondiglia, T. J. Bunning and W. W. Adams, Development of Photopolymer/Liquid Crystal composite Materials for Dynamic Hologram Applications, Proc. SPIE Vol. 2152, paper 38.

3. V. P. Tondiglia, L. V. Natarajan, R. L. Sutherland, T. J. Bunning and W. W. Adams, Volumn holographic image storage and electro-optic readout in a polymer dispersed liquid crystal film, Opt. Lett. v. 20, p. 1325, 1995.

4. R. L. Sutherland, L. V. Natarajan, V. P. Tondiglia, T. J. Bunning and W. W. Adams, Switchable holograms in a new photopolymer-liquid crystal composite, Proc. SPIE, Vol. 2404, p. 132, 1995.

5. R. L. Sutherland, L. V. Natarajan, V. P. Tondiglia, T. J. Bunning and W. W. Adams, Electrically switchable volumn gratings in PDLC, Appl. Phys. Lett., Vol. 64, p. 1074, 1994.

6. U. S. Patent 4,938,568. July 3, 1990. John D. Margerum, et al.

7. U. S. Patent 5,096,282. March 17, 1992. John D. Margerum, et al.

"Electronically switchable Bragg grating or (ESBG)" is defined as any of an extensive range of devices and device geometries realized utilizing a film of the aforementioned holographically processed polymer/liquid crystal composite.

ESBG's based on the materials technology of holographically processed polymer/liquid crystal composites provide a superior and efficient method of realizing switchable gratings. However, there are special demands for these materials systems. In particular, holographic polymerization means that a solution containing prepolymer and liquid crystal and other

ingredients is prepared in a thin layer and then exposed to interfering laser beams which initiate a polymerization and diffusion process. This manufacturing technique results in microdroplets of liquid crystal being formed, distributed into planes that follow the interference fringe structure of the incident light, and which are then permanently frozen into a matrix of transparent polymer. By application of an electric field, the liquid crystal molecular axes can be rotated within the droplets, with the overall effect of varying the refractive index contrast between polymer and liquid crystal. The net result is an ESBG having an electronically switchable diffraction efficiency.

For many applications, relatively simple holograms or gratings recorded optically in such media by laser interference are sufficient. Examples of such applications include simple regular planar gratings, lenses copied holographically from actual pre-existing lenses, or holograms intended for visual display. More advanced applications may require diffractive elements to be calculated and modeled by computer, which greatly expands the range of possible optical functions. For example, the functions of lens elements that would require difficult or impossible aspheric fabrication can be duplicated by computer generated diffractive structures. As a second example, Dammann gratings to divide a laser beam into an array of spots are computer designed and generated. Typically, computer generation results in the production of a two dimensional mask which encodes the diffractive function envisioned by the designer. For purposes of this application, a "mask" is defined as:

> A two dimensional distribution of spatially varying phase(phase mask) or transmittivity (gray scale mask) or a combination of both, recorded in a partly or fully transparent material. A grey-scale mask is a recording on a thin or planar medium of a continuous or pixilated pattern whose local value varies in absorption or grey-scale. Methods of recording gray scale masks include silver halide films, photosensitive glasses or polymers exposed by laser direct writing, by CRT imaging devices, or by other techniques of photolithography. A phase mask is a recording on a thin or planar medium of a continuous or pixilated pattern whose local value varies in optical phase delay, for example through a relief structure in a transparent medium such as glass or fused silica. A phase mask may be produced through multistep e-beam lithography, by e-beam direct write onto electron resist media, by laser direct write into photoresist , or by other

techniques known to the art of computer generated diffractive optics and microlithography.

The problem in converting such a mask into a switchable version depends on methods specific to the materials technology utilized. The special requirements of ESBG recording include the need to expose the ESBG in a parallel process, the necessity for recording a submicron periodicity even when the mask contains only larger features, the need to convert a two dimensional mask to a three dimensional volume hologram, and the fact that the appropriate wavelength for use of an ESBG may be substantially different than the wavelength at which the ESBG is polymerized.

More specifically, because of the limitations imposed by the polymerization process, the design of ESBG's has heretofore been limited to diffractive elements or holograms amenable to recording by purely optical methods involving exposure to laser interference patterns. The range of applications for ESBG's could be greatly extended if a method were developed for realizing computer generated diffractive designs. A conventional method of recording computer generated submicron patterns into typical photoresist or photopolymer materials is by means of laser direct writing, using a tightly focussed laser beam writing in a raster scan fashion. However, this approach is ineffective with the materials used for ESBG's. This is due to the specific polymerization dynamics of this composite medium, which depends on short range diffusion of liquid crystals from the bright into the dark fringe areas during the time span of exposure to laser radiation. This is a parallel process that requires an interference pattern to be applied simultaneously to the entire film volume and maintained for some time, typically 1-3 minutes. Also, because of the short physical scale of the diffusion process that is found to result in optimum diffraction efficiencies, it is necessary for the scale of the pattern applied to the polymer/liquid crystal composite to contain periodic structures on a scale of approximately 0.2-1.0 micrometer. This applies even if the diffractive element to be recorded has larger features, which for some applications may be on the order of 100-300 micrometers or larger. Direct recording by contact printing of such relatively large scale patterns would yield ESBG's with very low diffraction efficiency and would be useless. Finally, the difference in the wavelength at which ESBG's are recorded and the wavelength at which they are reconstructed in use imposes a limitation for some purposes.

ESBG technology could therefore yield a wider range of useful functions, such as switchable focus lenses, switchable beam distribution arrays, switchable waveguide couplers, and numerous other applications provided one or more appropriate recording approaches could be developed which are adapted to the unique requirements of this composite medium and which , in particular, overcome the various limitations discussed above.

Summary Of The Invention

In accordance with the above, this invention provides a method for fabricating a holographically processed polymer/liquid crystal composite (HPP/LCC) containing a complex diffraction grating. The method involves the steps of providing a mask containing a diffractive optical element; and illuminating a polymer/liquid crystal composite film with radiation in the form of two interfering plane waves at a selected angle to each other, at least one of the plane waves passing through the mask to produce a three-dimensional interference pattern in the film having generally submicron carrier features modulated by the optical element of the mask. The carrier feature will preferably have a period which is substantially in the 0.2 to 1.0 μm range, and the diffractive optical pattern formed in the film will have this submicron period even though the optical element of the mask may have a much larger period, for example at least 5 μm, and in some instances over 100 μm.

For some embodiments of the invention, there is at least one mask, and at least one of the plane waves passes through the at least one mask before substantial interference occurs between the waves. In one species of this embodiment, the plane waves are at selected angles to the plane of the film, with one of the plane waves passing through the mask before interfering with the beam. For another species of this embodiment, one of the beams is substantially normal to the plane of the film and passes through the mask, the mask has a periodic two-dimensional pattern as its optical element, and the mask is spaced by a distance $Z=2P^2/\lambda$ from the film, P being the period of the mask pattern and λ being the wavelength of the beam passing through the mask. For either of these species, the mask may be a gray scale mask or a phase mask.

For another embodiment, the plane waves pass through the mask as an interference pattern between the waves, the mask being in contact with the film when the interference pattern passes therethrough for a preferred form of this embodiment. For this embodiment, the mask is preferably a gray scale mask.

For all embodiments, the diffractive optical element for the mask is preferably computer designed and recorded. Finally, where the HPP/LCC is an ESBG, the step of capturing the film between a pair of transparent electrodes is also performed at a selected point in the process.

The invention also includes an ESBG formed by the steps of: (a) providing a mask containing a diffractive optical element; (b) illuminating a polymer/liquid crystal composite film with radiation in the form of two interfering plane waves at a selected angle to each other, at least one of the plane waves passing through the mask to produce a three-dimensional interference pattern in the film having submicron carrier features modulated by the optical element of the mask; and (c) capturing the film between a pair of transparent electrodes, with step (c) being performable at any point in the process. The ESBG may, for example, be a switchable focus lens or a switchable focus microlens array.

The foregoing and other objects, features and advantages of the invention will be apparent from the following, more particular description of preferred embodiments of the invention as illustrated in the accompanying drawings.

In the Drawings

Fig. 1 is a diagram of a simple mask suitable for use in practicing the teachings of this invention.

Figs. 2-4 are schematic illustrations of various optical component fabrication techniques in accordance with the teachings of this invention.

Detailed Description

As indicated earlier, there are applications for ESBG's where the holographic pattern required is sufficiently complex as to require the use of a computer generated mask having a diffraction grating formed therein which is sufficiently complex and not realizable by simply interfering two plane laser beams as is normally done. Therefore, in accordance with the teachings of this invention, the HPP/LCC for such ESBG is formed by imaging a complex mask, which mask is preferably computer generated and contains a desired complex pattern to be imaged on a film of the polymer/liquid crystal composite by use of a pair of interfering laser wavefronts. By suitably selecting the angle of such wavefronts to each other, the desired submicron holographic pattern can be obtained for the HPP/LCC in order to achieve optimum diffraction efficiency therefrom. with this carrier pattern being modulated by the pattern from the

mask in order to achieve the desired optical effect. The actual technique utilized to implement this method determines the type of mask which can be used (i.e. a gray scale mask, a phase mask or both), and also determines whether reading out of the ESBG can be performed at a wavelength other than that used for recording or whether recording and readout must be performed at the same wavelength. Thus, the technique utilized for recording the holographic image in the HPP/LCC is to least at some extent determined by the mask to be utilized and by the wavelengths at which recording and reading are to be accomplished.

Fig. 1 illustrates a simple mask 10 having a standard concentric circular pattern which might be utilized as a mask in practicing the teaching of this invention, although for most applications, a far more complex mask, for example one suitable for generating a microlens array, would be utilized. Such mask would typically be generated by computer calculation and preperation of the mask as the output from such calculation, the mathematical and computational techniques for analyzing and generating diffractive designs to accomplish specific optical function being known in the art and being the subject of extensive scientific and engineering literature.

Fig. 2 illustrates a method for generating an HPP/LCC in accordance with the first embodiment of the invention. The mask 10' used for this embodiment of the invention can only be a gray scale mask, a phase mask not being suitable for this embodiment. Such a mask, even if computer generated, would typically contain features no smaller than 5 μm, and in many applications might have features with a period of 100 μm or more. However, as discussed earlier, since in order to achieve high diffraction efficiencies with such composites, submicron periods, normally in the range of 0.2 to 1.0 μm are generally required. The mask 10' can therefor not normally be used to, for example, directly record the mask image on a polymer/liquid crystal composite film 12. Instead, as shown in Fig. 2, the mask 10' is first placed in contact with film 12. The mask is then illuminated by a pair of interfering beams or wavefronts 14A, 14B at an angle to each other to produce an interference pattern at the mask having submicrometer features. Wavefronts 14A and 14B are preferably laser wavefronts at the preferred recording wavelength for the film material which is for example 488 μm. The wavelength actually utilized for recording will depend on the photsentizer used in the HPP/LCC and possibly on other characteristics of the HPP/LCC composites. The angle between the wavefronts 14 may be adjusted to obtain an interference pattern having the desired submicrometer features, which angle will vary with application. The mask provides an envelop that modulates, by gray scale, the

volumetric interference field produced by the interfering laser beams, with the result that the mask image together with a uniform carrier of submicrometer spatial-global period are simultaneously applied.

After completion of the polymerization, or at any time therebefore, suitable electrodes, for example transparent electrodes, may be applied to the HPP/LCC film 12, for example by containing the film between transparent plates containing such electrodes, to form an ESBG structure which, after polymerization, contains both the carrier and modulating pattern encoded as a volume transmission hologram. According to the principles of holographic reconstruction, application of an appropriately expanded laser beam, which for this embodiment may be of a wavelength other than the wavelength utilized for recording the hologram resulting in reconstruction of the wavefront intended by the computer design of the mask; however, such reconstruction will be off-axis to the normal to the ESBG plane by the Bragg angle θ such that $\sin \theta = \lambda / 2\Lambda$ where λ is the wavelength of the laser beam or other wavefront utilized to read out the ESBG and Λ is the period of the carrier in the grating (i.e. the period of the interference pattern recorded therein).

As indicated above, the method shown in Fig. 2 is limited in that only a gray-scale mask may be utilized as a mask 10' in practicing this method, and a phase mask may not be utilized. Fig. 3 shows a technique which may be utilized with a mask 10 which is either a gray scale mask or a phase mask; however, when recording is done utilizing the method of Fig. 3, read out or reconstruction can be accomplished only at the wavelength at which recording was performed. The technique utilized in Fig. 3 is sometime referred to as Fresnel holography rather than contact holography as for the technique of Fig. 2. The mask 10, which is shown in Fig. 3 as a Fresnel lens but may be a flat mask, is illuminated by one of the beams or wavefronts 14A at some distance from film 12, producing a partially developed wavefront at the plane of the film, where this wavefront meets and interferes with laser plane wave beam 14B acting as a reference wave. This method essentially forms a hologram of a hologram, and is particularly advantageous for situations where it is desired for the mask encoded image to be reconstructed at a different plane than the ESBG itself. The distance of mask 10 from film 12 controls the distance at which the reconstruction occurs from the plane of the ESBG in manners known in the art. However, as indicated above, ESBG's formed in accordance with the method of Fig. 3 can only be accurately read-out or reconstructed by a laser beam or other wavefront at the same wavelength as the recording wavefronts 14.

Fig. 4 illustrates a fabrication technique for an HPP/LCC film 12 which does not have the limitations of either of the prior embodiments. In particular, the mask 10 utilized to practice this embodiment may be either a gray scale or a phase mask and the wavelength of reconstruction for an ESBG utilizing film 12 need not be the same as the wavelength of the recording beams 14. More specifically, while the technique shown in Fig. 3 will result in severe chromatic aberration and distortions if the wavelength used for reconstruction of the complex hologram is different than that used for recording, no such aberration or distortions occur when recording is performed in accordance with the method of Fig. 4.

The method of Fig. 4 requires that the mask 10" utilized, which mask may be either a gray scale mask or a phase mask, be periodic (i.e contain a two-dimensional pattern that repeats it itself in the plane of the mask with a period P). One example of such a pattern is a two-dimensional regular array of microlenses. The Talbot effect (Lord Rayleigh, Philosophical Magazine, V.11) is a known diffractive phenomenon whereby a periodic two-dimensional pattern illuminated by a coherent wavefront such as a laser will reproduce itself exactly at a distance Z from the mask, where $Z=2P^2/\lambda_r$, λ_r being the wavelength of the recording beam. Thus, a periodic array of microlenses with a period P=100 microns illuminated by laser light with a wavelength λ of 0.488 microns, will reproduce itself in the Talbot plane at a distance Z of 41 mm from the mask. This phenomena is utilized in Fig. 4 to record an HPP/LCC film 12 with a periodic mask 10" which may be either a phase mask or a gray scale mask, which HPP/LCC does not have the chromatic aberration problem discussed above when utilized in ESBG. Beam 14A illuminates film 12 through mask 10" having a periodic pattern formed therein. Mask 10" is a the Talbot distance Z from film 12 and beam 14A is substantially normal to film 12. A second off-axis reference beam 14B interferes with beam 14A to provide the submicrometer carrier spatial frequently required to meet the periodicity requirements to obtain diffractive efficiency. An ESBG formed in accordance with the method of Fig. 4 will reconstruct when illuminated with a beam which does not need to be at the same wavelength as to recording beams 14, but which is at the angle of the reference beam 14B, will reconstruct the diffractive element represented by the mask in a plane normal to the plane of the ESBG.

While three methods for recording an HPP/LCC film suitable for use in an ESBG have been described above, which techniques permit complex three-dimensional holographic patterns to be recorded with a small enough periodicity to achieve high diffraction efficiency from the ESBG, the methods disclosed are by way of illustration, only, and other methods which utilize

interfering wavefronts to produce a carrier optical pattern in the HPP/LCC film modulated by a complex pattern contained in a mask might also be utilized. Further, while the invention has been described with reference to films and components containing Bragg gratings, components using HPP/LCC materials other than Bragg grating, for example, Raman-Nath gratings may also be utilized. Thus, while the inventor has been particularly shown and described above with respect to preferred embodiments, the foreign and other changes in for and detail may be made therein by those skilled in the art without departing from the spirits and scope of the inventors, and the invention is to be limited only by the appended claims.

CLAIMS

1. A method for fabricating a holographically processed polymer/liquid crystal composite (HPP/LCC) containing a complex diffraction grating comprising the steps of:

   (a) providing a mask containing a diffractive optical element; and
   (b) illuminating a polymer/liquid crystal composite film with radiation in the form of two interfering plane waves at a selected angle to each other, at least one of said plane waves passing through said mask to produce a three-dimensional interference pattern in the film having submicron spatial carrier features modulated by the optical element of the mask.

2. A method as claimed in claim 1 wherein there is at least one of said mask, and wherein said at least one plane wave passes through the at least one mask before substantial interference between said waves.

3. A method as claimed in claim 2 wherein said plane waves are propagated at angles to the plane of said film, and wherein one of said plane waves passes through the mask before interfering with the other beam.

4. A method as claimed in claim 2 wherein one of said beams is substantially normal to the plane of the film and passes through the mask, wherein the mask has a periodic two dimensional pattern as its optical element, and wherein the mask is spaced by a distance $Z=2P^2/\lambda$ from the film, P being the period of the mask pattern and λ being the wavelength of said one beam.

5. A method as claimed in claim 2 wherein said mask is one of a gray scale mask and a phase mask.

6. A method as claimed in claim 1 wherein said plane waves pass through said mask as an interference pattern between the waves.

7. A method as claimed in claim 6 wherein the mask is in contact with the film when step (b) is performed.

8. A method as claimed in claim 6 wherein said mask is a gray scale mask.

9. A method as claimed in claim 1 wherein step (a) includes the step of computer designing and recording a diffractive optical element for said mask.

10. A method as claimed in claim 6 wherein said spatial carrier features have a period which is substantially in the 0.2 to 1.0 μm range.

11. A method as claimed in claim 10 wherein the optical element of said mask has a period of at least 5 μm.

12. A method as claimed in claim 1 wherein said HPP/LCC is an ESBG, and including the step, performed at any point in the process, of capturing the film between a pair of transparent electrodes.

13. An ESBG formed by the steps of:

(a) providing a mask containing a diffractive optical element; and
(b) illuminating a polymer/liquid crystal composite film with radiation in the form of two interfering plane waves at a selected angle to each other, at least one of said plane waves passing through said mask to produce a three-dimensional interference pattern in the film having submicron carrier features modulated by the optical element of the mask; and
(c) capturing the film between a pair of transparent electrodes, step (c) being performable at any point in the process.

14. An ESBG as claimed in claim 13 wherein said spatial carrier features have a period which is substantially in the 0.2 to 1.0 μm range.

15. An ESBG as claimed in claim 14 wherein the carrier features are modulated by optical elements of the mask having a period of at least 5 μm.

16. An ESBG as claimed in claim 13 wherein the ESBG is a switchable focus lens.

17. An ESBG as claimed in claim 13 wherein the component is a switchable focus microlens array.

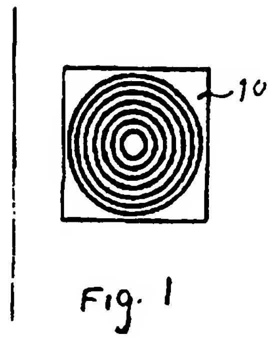

Fig. 1

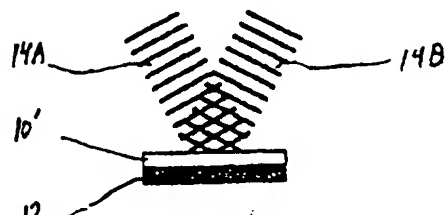

Fig. 2

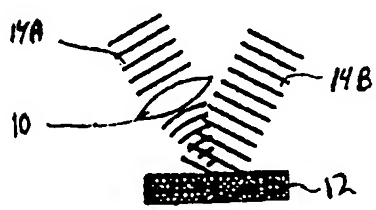

Fig. 3

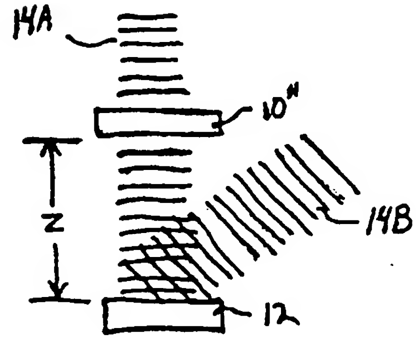

Fig. 4

INTERNATIONAL SEARCH REPORT

International application No.
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A. CLASSIFICATION OF SUBJECT MATTER

IPC(6) : G03H 1/04, 1/08, 1/02; G02B 5/32, 5/18
US CL : 349/202, 201; 430/1, 2, 290; 359/1, 12, 3, 7
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 349/202, 201; 430/1, 2, 290; 359/1, 12, 3, 7

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

None

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

APS; liquid crystal# or LC# with holograⅶ or grating#

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	Caulfield et al., "Applications of Holography" 1970, Chapter 10, pages 91-94	9
Y	Sincerbox, G.T., "Formation of Optical Elements by Holography", IBM Tech. Discl. Bull. August 1967, Vol. 10, No. 3, pp. 267-268.	16 and 17
Y	US 4,806,442 A (SHIRASAKI et al.) 21 February 1989, Figure 4 and col. 9, lines 3-44, col. 10, lines 20-32 and 43-51.	1-11
Y	US 5,340,637 A (OKAI et al.) 23 August 1994, col. 1/lines 40-46, col. 4, line 66-col. 5, line 13 and embodiments 7 and 9.	4,5-810 and 11

[X] Further documents are listed in the continuation of Box C. [ ] See patent family annex.

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C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
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